Radiometric Autonomous Navigation Fused with Optical for Deep Space Exploration

Completed Technology Project (2016 - 2019)

Project Introduction

Develop the algorithms and prototype software for computing robust trajectory solutions that combines one-way onboard radiometric measurements with optical imagery that is part of autonomous navigation system for deep space exploration. With the advent of NASA's Deep Space Atomic Clock, operationally accurate and reliable one-way radiometric data sent from a radio beacon (i.e., a DSN antenna or other spacecraft) and collected using a spacecraft’s radio receiver enables the development and use of autonomous radio navigation.   Autonomous navigation using NASA’s AutoNav software system (developed by JPL) has been a critical technology for many deep space missions, including Deep Space 1, Stardust, and Deep Impact. For these missions, autonomous navigation was conducted using passive optical imaging of nearby bodies with an on-board camera system. Optical data provides strong angular information about a spacecraft’s ‘plane-of-sky’ relationship to the object being imaged. Range (or ‘line-of-sight’) information, orthogonal to the plane-of-sky, is more difficult to determine from optical data due to parallax issues of observations taken from far distances. A more direct measure of line-of-sight is obtained with radiometric tracking of range and Doppler. These measurements compliment the optical data such that, when combined with optical, yield a more complete, almost kinematic, robust solution for a spacecraft’s absolute position in space. Indeed, the fusion of these two data types is central to an autonomous deep space navigation capability that will be needed for a wide range of future missions – examples include autonomous landings on small or large bodies, human asteroid and Mars explorations, and efficient navigation for future orbiters and interplanetary craft.

Space explorers – robotic or human - need to safely navigate the depths of the solar system with the tools available to them. They need reliable, abundant, and timely information telling them their trajectory so that they can plan an effective course. With both the number and complexity of robotic mission operations increasing, and the advent of solar system exploration by humans, there is a need to have robust, fault tolerant, on-board, and automated navigation. The DS-1, Deep Impact, and Stardust missions proved the viability of autonomous navigation, that was even mission critical for defined, short lived mission phases (i.e., chasing the impactor for DI, or comet flyby for Stardust). However, autonomous navigation has not become routine. It is not yet safe enough to ‘cut the cord’ with Earthly bound navigators - breakthroughs are required. Another benefit that could be realized with the deployment of reliable autonomous navigation is a significant reduction in DSN utilization via combining optical and radio (with DSAC) data thus reducing tracking requirements in cruise, and, at places such as Mars, taking full advantage of Multiple Spacecraft per Aperture for tracking.

This technology task is developing a new extensions to JPL’s AutoNav that will provide qualitatively new capabilities, crossing the threshold into the realm of reliable and safe on-board navigation by capitalizing on the technology

JPL_IRAD_Activities Project

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advancement provided by DSAC for conducting one-way radio navigation. DSAC coupled with a capable radio (such as the Universal Space Transponder in development) solves the measurement problem – routine collection of Doppler and, with some enhancements to the DSN, range are now possible. However, AutoNav cannot yet process this data; enhancements to AutoNav's measurement modeling, dynamic modeling, and state estimation capabilities are required. The requisite models exist today in JPL's ground software, but these do not take into account the realities of an onboard implementation where computational resources are limited and trajectory solution trending/assessment must occur for specified periods without human intervention. Sufficient models, robust and adaptive algorithms, and solution assessment must be determined and engineered for a successful onboard implementation.

The core of this task is analyzing, designing, and developing a protype onboard radio navigation capability and integrating it into AutoNav's existing capabilities for processing optical imagery. Key factors that will influence how and what we do:

- Radiometric data has information along only one axis (line of sight), and it does not contain as much in any given measurement as compared to its optical counterpart (which has plane of sky sensitivity to the two orthogonal dimensions). However, the radiometric data are an order of magnitude more precise in that dimension as compared to the optical plane-of-the-sky measurements. As a result, radio navigation solutions are more sensitive to modeling fidelity and modeling errors, and will require careful consideration of appropriate models. Examples of modeling issues to consider include gravity field size for an orbiting mission, atmospheric calibration fidelity for planetary approach, or the degree of integration to the spacecraft attitude system. This research is developing a sufficient set of dynamic and measurement model for use in onboard navigation in multiple flight regimes – cruise, approach, orbit, small and large body.
- Radiometric data combined with optical provide position information along multiple axes (not equally so) plus, with Doppler, rate information along the line of sight. Navigation solutions that combine both data types will be more robust, but each will have strengths in different flight regimes. This task is investigating the role that each data type plays in the solution process to aid in identifying sufficient modeling.
- Operational robustness requires fault tolerant solutions – radio and optical complement each other and provide for a natural fault tolerance (different observation systems, different observation quantities). To take full advantage of this will require advanced filtering techniques. Examples include adaptive filtering with multi-model filter banks, measurement pre-processing to determine outliers and trends, post-process solution assessment (consistency and stability), and alternate filter algorithms such as Unscented Kalman filtering or Sigma Point filtering. This task is reasearching these options to determine a best mix of capabilities for implementation.

Organizational Responsibility

Responsible Mission Directorate:

Mission Support Directorate (MSD)

Lead Center / Facility:

Jet Propulsion Laboratory (JPL)

Responsible Program:

Center Independent Research & Development: JPL IRAD

Project Management

Program Manager:

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This effort will require restructuring the architecture of the existing AutoNav software as it is, essentially, a point design that is not easily extended. A key aspect of this restructuring is to examine JPL's more general purpose MONTE navigation toolkit and the Optical Navigation Program (ONP) and integrate selected components into AutoNav. This will facilitate the addition of not only radiometric data processing but also the more advanced filtering methods. We propose to generalize AutoNav to allow processing of multiple data types, with multiple filter instances, and to maximize efficiency of storage and computations on representative flight processors and memory that we will test via emulation.

The state of the art in autonomous space navigation is JPL's AutoNav software that, currently, only processes optical data. The addition of radiometric data processing will be new. The closest analog is NASA GSFC GEONS and JPL's Real Time GIPSY software; however, these rely on GPS data and typically require a minimal set of GPS satellites to be in view in order to produce viable navigation solutions. These systems target orbital operations in the vicinity of Earth, and are not readily extensible to deep space operations. AutoNav is uniquely suited for processing radio data as it has been built around the deep space navigation paradigm.

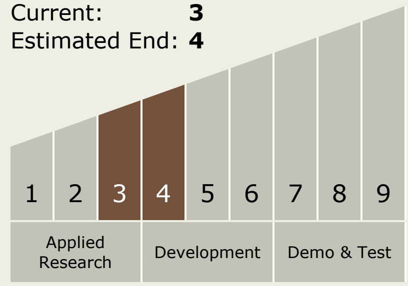
Anticipated Benefits

Robust onboard navigation will be required for future human deep space exploration of the solar system. This research will develop the foundational algorithms and prototype software needed to provide safe, robust onboard trajectory solutions for this exploration. Robotic missions could also benefit by having reliable onboard solutions that would enable accurate, realtime navigation for critical events such as flybys or planetary entry. Once proven, it could also be used to reduce the ground navigation support.

This technology has the potential to support commercial efforts to explore deep space.

Technology Maturity (TRL)

Start: **3**
Current: **3**
Estimated End: **4**



Technology Areas

Primary:

- TX17 Guidance, Navigation, and Control (GN&C)
  └ TX17.2 Navigation Technologies
    └ TX17.2.1 Onboard Navigation Algorithms

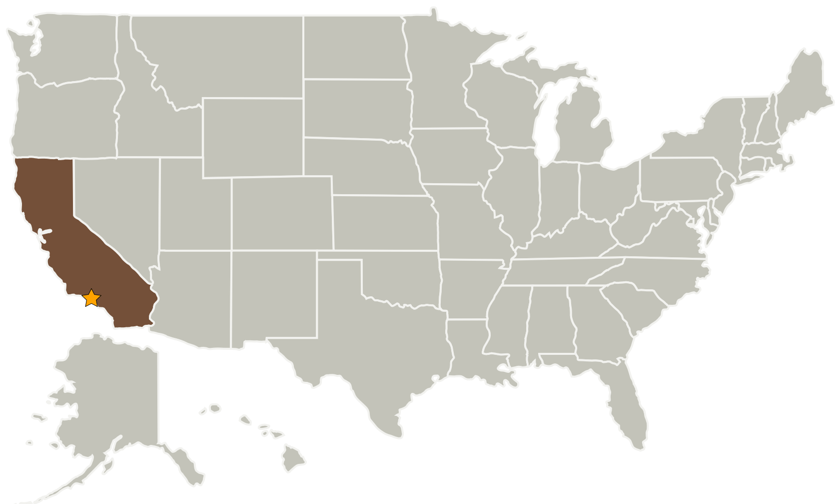
Target Destinations

The Moon, Others Inside the Solar System

Supported Mission Type

Projected Mission (Pull)

Primary U.S. Work Locations and Key Partners



Organizations Performing Work	Role	Type	Location
★Jet Propulsion Laboratory(JPL)	Lead Organization	NASA Center	Pasadena, California

Primary U.S. Work Locations
California

Images

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(https://techport.nasa.gov/image/28056)